How Plants Absorb Nutrients from the Soil

16

16.1 Introduction

In the introduction of Chap. 8 some aspects of the nutrient uptake dynamics of plants were presented, summarized in Eq. (8.1). In that chapter we were concerned with the characterization of *M* (solution) and the processes of nutrient transfer in the soil. In this chapter, we will develop the subject a little further, discussing the flow of soil ions to the roots and we will introduce the mechanisms of nutrient uptake by plant roots.

16.2 Movement of Nutrients from the Soil to the Surface of Roots

The solid fraction of the soil, both mineral and organic, is the reservoir of nutrients for the plant. For a satisfactory development of the plant, it is necessary that the **ion activity** of each nutrient is adequate in the solution of the soil. This activity depends, above all, on the absorption by the roots and their "release" by the solid phase. The release of nutrients from the soil solid fraction is an important chapter in the study of soil fertility. In Chap. 8, we describe the phenomena of adsorption and ion exchange and we will not discuss further this matter. Let's just draw the reader's attention to the fact that nutrients, in their different forms, are bound to the solid phase with different energies. Thus, for example, NO_3^- and Cl^- are practically free of adsorption in most soils that have excess negative charges; K^+, Ca^{2+}, Mg^{2+}, and NH_4^+ are adsorbed electrically by clay minerals and organic matter; Fe^{3+} and Cu^{2+} can form complexes and chelates; the P can also form complexes of high insolubility with the oxides of Al and Fe; etc. The rate of release of these ions into the liquid phase depends on all these forms of adsorption. Once in the liquid phase, each nutrient can be absorbed by the roots, and this absorption depends on a series of problems that will be discussed later in this chapter. To be absorbed by the plant, a nutrient must be present in soil solution, and in contact with the active surface of the root system, in a form that can be absorbed and utilized by the plant. This "available" form of the different nutrients has been the object of attention of the soil chemists, being extensive the literature on the subject. In general, it can be said that the main factors controlling the transition from *M* (solid) to *M* (solution) (see Eq. 8.1) are solubility and oxidation potential. Sposito (1989) is a complete text on these physicochemical aspects of the soil.

Once in solution, two processes are responsible for the transfer of a nutrient from the soil to the plant: **diffusion** and **mass transport**. The diffusion comprises transport due to gradients of

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chemical potential, measured by the activity of the ion in question in the soil solution; and the mass transport refers to all transport of ions carried along by the flow of water in the soil. Olsen and Kemper (1968) present an extensive theoretical discussion about the different factors involved in these ion transport processes.

16.3 Diffusion

The fundamental equation of the diffusion of a solute in the soil in given direction x is the **Equation of Fick**, seen in Chap. 8:

$$j_d = -\underbrace{\left[\theta D_0 \left(\frac{L}{L_e}\right)^2 \alpha\gamma\right]}_{D} \left(\frac{\partial C}{\partial x}\right) \qquad (16.1)$$

where j_d is the flux density of a given ion in the soil by diffusion and x is the position coordinate measured directly in the soil. As already mentioned, the volume-based soil water content θ is included in the equation because it measures the available cross-section area for the flow, because the movement occurs only within the solution. In a cross section of soil A, only "$\theta \cdot A$" is available to the solution flow. The other factors mentioned in Eq. (16.1) were discussed in Chap. 8.

Thus, for example, if at a point P of the soil the concentration C_P of NO_3^- is 6.2 mg L^{-1} and at another point M, distant from $\Delta x = 10$ cm of P, the C_M concentration of NO_3^- is 2.9 mg L^{-1}, there will be a flow of NO_3^- from P to M, which can be calculated by the Fick equation. Let the diffusion coefficient D of NO_3^- in the soil be equal to 0.54×10^{-5} cm^2 s^{-1}. The concentration gradient $\partial C/\partial x$ can be approximated by finite differences $(C_M - C_P)/\Delta x$ and thus we have:

$$j_d = \frac{-0.54 \times 10^{-5}\left(2.9 \times 10^{-3} - 6.2 \times 10^{-3}\right)}{10}$$
$$= 1.78 \times 10^{-8}\,\text{mg}\,\text{cm}^{-2}\,\text{s}^{-1}$$

In this example, P could be a generic point of the soil that is 10 cm from an absorbent root, on which is M. By diffusion, j_d would be the ionic flux density from the soil to the root.

16.4 Mass Flow

The transport of nutrients by **mass flow**, also called convection flow, depends strictly on the flow of water, since it comprises the amount of nutrients carried by the water per unit cross section of the flow per unit time. The water flux density q is conveniently described by the **Darcy-Buckingham equation** discussed in Chap. 7:

$$q = -K(\theta)\frac{\partial H}{\partial x} \qquad (16.2)$$

where q is the water flux density (L H_2O m^{-2} day^{-1}), $K(\theta)$ the hydraulic conductivity of the soil (mm day^{-1}), and $\partial H/\partial x$ the hydraulic potential gradient (m m^{-1}).

Given the water flux density q, the mass flow density j_m of a nutrient can be calculated by the expression:

$$j_m = q \cdot C \qquad (16.3)$$

C is the nutrient concentration in the water. If, as an example, the water flux is 0.2 L m^{-2} day^{-1}, or 0.2 mm day^{-1}, and the concentration of NO_3^- in the water is 6.2 g L^{-1}, we will have:

$$j_m = 0.2 \times 6.2 = 1.24\,\text{mg of } NO_3^-\,\text{cm}^{-2}\,\text{day}^{-1}$$

In this example, if the water flow in the soil toward the roots, provoked by the evaporative demand of the atmosphere, would be q, the mass flow of nitrate into the plant would be j_m.

16.5 Relative Importance of Root Extension in Relation of Nutrient Absorption

The two processes described separately above occur simultaneously in the transport of nutrients from the soil to the plants. The magnitude of each process varies from situation to situation. In addition to these processes, plant nutrition is still

Table 16.1 Barber and Olsen's example of the sharing among root interception, mass flow, and diffusion, for a maize crop

		Quantity supplied by:		
Nutrient	Maize requirement in kg ha^{-1}	Root interception	Mass flow	Diffusion
N	190	2.2	188.0	0
P	39	1.1	2.2	35.8
K	196	4.5	39.2	152.5
Ca	39	67.3	168.2	0
S	22	1.1	21.3	0
Mo	0.01	0.001	0.02	0

affected by the extension of the root system of plants. The question can be posed as follows: either the nutrient moves from the soil to the root (diffusion and mass transport) or the root "directs" its growth to a point where it encounters the nutrient (**root interception**). By such an affirmative, we do not mean that roots have directed growth; they grow randomly and, as they grow, they explore new volumes of soil where they meet nutrients.

The relative importance of root interception, diffusion, and mass flow in maintaining an adequate concentration of a nutrient close to root absorption surfaces is difficult to determine. Even for a given soil-plant condition, the relative importance of each process varies with the time of day and point to point within the soil profile. Barber and Olsen (1968) made the first efforts to determine the contribution of each of these three processes, starting from very simplified hypotheses. Some of their examples are shown in Table 16.1.

16.6 Influence of Soil Physical Condition on the Transport of Nutrients

16.6.1 Soil Water Content

Soil water content varies greatly during the vegetative cycle, decreasing gradually in quantity while evapotranspiration proceeds, increasing steeply with rainfall or irrigation. The description of the water regime in a crop is a problem that requires the knowledge of water content and water potential in space and time, which is done by the water balance (Chap. 15). In the same way, from the nutritional point of view, it is important to know the soil water content and its matrix potential. In general, the greatest use of nutrients by plants occurs when soil water contents are kept as high as possible (close to field capacity), but do not cause aeration and temperature problems.

Soil water content, when appropriate, allows for potential transpiration by plants; the nutrients are absorbed by mass flow to the root surface and, in many cases, entering into the root and then to the upper part by the xylem. The mass flow of nutrients, directly proportional to the flow of water in the soil, described by the Darcy-Buckingham equation (Eq. 7.3, Chap. 7), is extremely affected by soil water content conditions. The hydraulic conductivity $K(\theta)$, which expresses the soil hydro-physical property of transmitting water, is very much affected by soil water contents. It is drastically reduced with relatively small decreases in θ; in general the relation $K(\theta)$ can be described by an exponential function. A K reduction of 100–1000 times is common for a 5% decrease in soil water content. Also, the potential gradient $\partial\Psi/\partial x$ is important. Often a considerable gradient implies in a reasonable flow despite low hydraulic conductivity of the soil. Roots, removing water from the soil, diminish the water potential increasing the gradient and allowing an adequate flow of water and nutrients, even for conditions of small K.

As seen above, the soil nutrient mass flow to the plants is affected by the transpiration, which in turn depends on the atmospheric conditions and the soil water content that affects the

hydraulic conductivity of the soil and the potential gradient. With these variations in space and time, the description of the phenomenon becomes complicated. Thus, the results of most research on the subject, such as the early work of Barber and Olsen (1968), presented in Table 16.1, cannot be generalized. An updated text on the dynamics of nutrients in the soil-plant system is that of Havlin et al. (2014). The authors discuss the importance of the presence of **available water** in the soil for the **nutrient mass flow** from the soil to the plants, emphasizing that the **availability of nutrients** is characterized by diffusion and mass flow in the soil, factors directly related to soil water content. Beyond this topic, Havlin et al. (2014) deal in depth with aspects related to soil fertility and plant nutrition. With the same soil and the same plant, under different conditions, opposite results can be obtained. Soil moisture also affects the diffusion of nutrients. The main effect is to reduce the area available to the flow, when θ decreases. In addition, the effective path of diffusion increases with the decrease of θ, noting also significant increases of viscosity and negative adsorption γ. Porter et al. (1960), Partil et al. (1963), and Olsen et al. (1965) were the main authors to initiate studies of the effect of θ on the diffusion coefficient D of different ions in the soil. In general, their data shows reduction of the order of 10 times in the values of D by a reduction of 10% of water content. Under field conditions, the variations of θ in space and time make it very difficult to analyze the phenomena. In the same way as we discuss the case of mass flow, generalizations cannot be made easily, in the case of nutrient diffusion. Each particular situation should be carefully considered, taking into account the influence of all of the factors together.

Soil water content also affects root development and thus "root interception" of nutrients. High levels of water affect the aeration of the soil, damaging root growth and low levels of water; impede the flow of water in the soil, increasing its matrix potential, to prevent water absorption; and also slow down root growth. Indirectly, variations in soil water content also imply variations in soil consistency (mechanical properties) of great importance in radicular penetration and management practices.

16.6.2 Soil Air

The importance of **soil aeration** in the nutrition of a typical upland crop is generally related to the activity of microorganisms and to root respiration. The supply of air to the soil is inversely proportional to the water supply, hence the dilemma: high levels of water are beneficial to nutrition, but may compromise the activity of essential microorganisms and root respiration. It is therefore necessary to determine an optimal point between the supply of water and air to the plants in the root zone. Most of the time, attention is focused on water supply, since aeration problems are often temporary, often unnoticed.

The aeration of the soil occurs mainly by diffusion. The diffusion equation of one gas into another is described by Eq. (9.2) (Chap. 9), varying only the magnitude of the diffusion coefficient. In this case:

$$D = (\alpha - \theta) D_0 \left(\frac{L}{L_e} \right)^2 \qquad (16.4)$$

where α is the total porosity of the soil (Eq. 3.12) and $(\alpha - \theta)$ the water free porosity β (Eq. 3.30).

Under unsaturated soil conditions, water occupies the smaller pores, leaving larger pores for air diffuse. The relationship between the diffusion coefficient D of a gas in the soil and its diffusion coefficient D in the air is not large and, for average conditions of field crops, the ratio is of the order of 0.6 times $(\alpha - \theta)$.

Studies of the effects of soil aeration on plant nutrition are found in a large number of studies. In the field, any restriction on aeration is generally temporary and difficult to diagnose, and its relationship with nutrition is quite complex. Anaerobic conditions can, for example, promote the availability of Fe, Cu, Mo, and Mn. Variations of oxidation potentials and pH, resulting from variations in aeration, increase the complexity of the problem.

16.6.3 Soil Texture

The textural analysis characterizes a soil from the point of view of the distribution of the solid particle size of the constituents. This distribution determines a **porosity** and arrangement of characteristic particles, which, in turn, will determine its water properties, such as hydraulic conductivity and the relationship between the soil water content θ and matrix potential (the **soil water retention curve**). These water properties directly or indirectly affect nutrient uptake processes, that is, diffusion, mass flow, and root interception. In general, however, for a given soil-plant system, the textural features are practically invariant over time. Its influence becomes more indirect, that is, by variations in the water content of the system.

16.6.4 Soil Temperature

The availability and absorption of nutrients are affected by the temperature in all phases of Eq. (8.1). The microbiological activity, solubility of compounds, diffusion coefficients, root absorption, root permeability, metabolic activity, etc., are all affected by **soil temperature** variations. Studies that relate temperature variations with root absorption and nutrient accumulation in plants are numerous and diversified, making a global interpretation difficult. In general, the biological activities in the soil increase with the increase of temperature, until a maximum around 30 °C. It appears that nutrient absorption has different temperature dependence for the various nutrients. For example, Walker (1969) has shown that maize seed growth has a maximum at a soil temperature of 26 °C, decreasing rapidly with the cooling or heating of the soil. The nutrient uptake, expressed as shoot concentration, has different response curves. In general terms, nitrogen uptake increases from 12 to 18 °C, decreases from 18 to 26 °C, and increases again from 26 to 34 °C. The phosphorus concentration decreases when the temperature increased from 12 to 25 °C and then increased when the temperature increased from 25 to 34 °C. Potassium increased more than 100% when soil temperature was raised from 12 to 18 °C, remaining constant at higher temperatures. On the other hand, Knoll et al. (1964) found an increase in the absorption of phosphorus with a temperature increase of 15–25 °C. These results demonstrate the complexity of the relationship between nutrient absorption and temperature. Even under very controlled conditions, it is difficult to determine causes of effects in experiments of this nature, making it virtually impossible to generalize about the effect of temperature on plant nutrition.

16.6.5 Root System

The type of root system and its distribution along the profile are also extremely important factors in nutrient absorption, especially in relation to radicular interception. Root grows mostly in the vegetative growth stages of annual crops because in the reproductive phases the plant devotes most of its energy for flowering and grain maturation. At the end of the vegetative phase, the root size is mostly defined, and in modelling the **effective root depth** is an important parameter. In relation to plant species, grasses, belonging to the family poaceae, for example, have a fasciculate root system, well distributed in the superficial layers of the soil. Dicotyledons have a pivotal root system, with a main root that can reach great depth. In general, its distribution follows an exponential model that decreases with depth. In addition, there are particular cases, such as coffee and orange, which proliferate absorbent roots around the crown skirt. Certain plants of the cerrado (the South American savanah) have a very deep pivotal root that reaches several meters in soil depth to guarantee their survival in prolonged periods of drought. Aspects of the influence of physical factors on root development under tropical conditions are discussed, among others, by Reichardt (1976, 1980).

16.7 Examples of Nutrient Movement in the Soil

Let us first consider the model of a root of radius $r = a$ in a constant water content soil in which the diffusion coefficient of a nutrient is D. Assume also that the root absorbs the nutrient only by diffusion, at a constant rate, in such a way that its concentration on the root surface is C_a. If the transport of nutrients occurs only by diffusion, what should be the concentration of the soil solution C at any point between A and B, the point B being located at the mean distance between two active roots (see Fig. 16.1).

In Chap. 14, we have already said that for problems of this kind, the cylindrical coordinates (see Fig. 14.4) fit better. In the same way, as it was made for the differential equation of water movement, we can write Eq. (14.8) as follows, using only the coordinate r:

$$\frac{\partial(\theta C)}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(rD\frac{\partial C}{\partial r}\right) \tag{16.5}$$

Since in the second member we have a derivative of a product of functions of r, that is, r and $D\partial C/\partial r$, by the chain rule we have:

$$\frac{\partial(\theta C)}{\partial t} = \frac{1}{r}\left(rD\frac{\partial^2 C}{\partial r^2} + \frac{\partial r}{\partial r}D\frac{\partial C}{\partial r}\right)$$

$$\frac{\partial(\theta C)}{\partial t} = D\left(\frac{\partial^2 C}{\partial r^2} + \frac{1}{r}\frac{\partial C}{\partial r}\right)$$

or

$$\frac{\partial C}{\partial t} = D'\left(\frac{\partial^2 C}{\partial r^2} + \frac{1}{r}\frac{\partial C}{\partial r}\right) \tag{16.6}$$

where $D' = D/\theta$.

It is opportune at this point to show the reader that Eq. (16.6) (cylindrical coordinates) is identical to Eq. (8.41a) (orthogonal Cartesian coordinates) for r tending to ∞, since in this case for very far distances two close radii become parallel and the coordinate r can be replaced by. If $r \to \infty$, $(1/r) = 0$, and:

$$\frac{1}{r}\frac{\partial C}{\partial r} = 0 \quad \text{and} \quad \frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial r^2}$$

Thus, it is verified that when $r \to \infty$, the cylindrical geometry tends toward the Cartesian.

Our problem, however, is a case of typically cylindrical geometry, in dynamic equilibrium, so that $\partial C/\partial t = 0$ and Eq. (16.6) becomes:

$$\frac{d^2 C}{dr^2} + \frac{1}{r}\frac{dC}{dr} = 0 \tag{16.7}$$

subject to the conditions:

$r = a$, $C = C_a$ and $r = b$, $C = C_b$

Let's assume Eq. (16.7) is of the type:

$$C = k_1 \ln r + k_2 \tag{16.8}$$

and thus it must satisfy Eq. (16.7), which contains a first derivative and a second derivative. Recalling that the derivative of ln r is $1/r$, the derivative of Eq. (16.8) is:

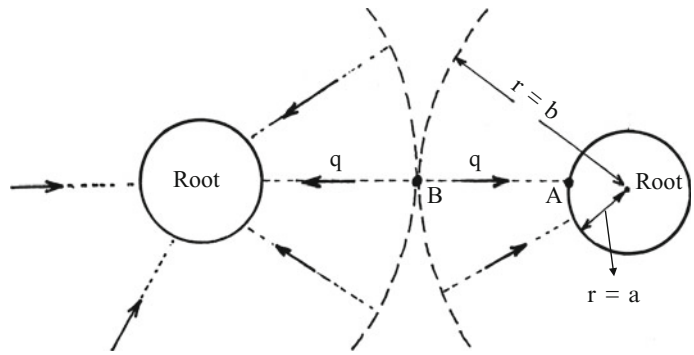

Fig. 16.1 Cut of two parallel roots indicating the radial flux q from point B to point A at the root surface

$$\frac{\partial C}{\partial r} = \frac{k_1}{r} = k_1 \cdot r^{-1}$$

and

$$\frac{\mathrm{d}^2 C}{\mathrm{d}r^2} = -k_1 \cdot r^{-2}$$

substituting these values in Eq. (16.7), we have:

$$-k_1 \cdot r^{-2} + \frac{1}{r} k_1 \cdot r^{-1} = 0$$

which confirms that Eq. (16.8) is the general solution of Eq. (16.7). The particular solution will be obtained using the boundary conditions:

$$C_a = k_1 \ln a + k_2$$

$$C_b = k_1 \ln b + k_2$$

So that:

$$k_1 = \frac{C_a - C_b}{\ln\left(\frac{a}{b}\right)}$$

and

$$k_2 = C_a - \frac{C_a - C_b}{\ln\left(\frac{a}{b}\right)} \times \ln a$$

and the particular solution will be:

$$C = \frac{C_a - C_b}{\ln\left(\frac{a}{b}\right)} \cdot \ln r + C_a - \frac{C_a - C_b}{\ln\left(\frac{a}{b}\right)} \cdot \ln a$$

or

$$C = C_a + \frac{C_a - C_b}{\ln\left(\frac{a}{b}\right)} \cdot \ln\left(\frac{r}{a}\right) \qquad (16.9)$$

With data for C_a, C_b, a, and b, it is easy to calculate C for any r between A and B, as the problem asks for besides C, we could still be interested in the input flow of nutrients to the root:

$$j_\mathrm{d} = -D \frac{\partial C}{\partial r}$$

Since $\partial C/\partial r = k_1/r$, for $r = a$, we have $\partial C/\partial r = k_1/a$, so that:

$$j_\mathrm{d} = -D \frac{k_1}{a}$$

It is often interesting to know the amount that penetrates the root per unit of length and time. The area of 1 cm radius root a is $(2\pi a)$ cm^2. So that:

$$j_\mathrm{d} = \frac{Q}{A \cdot t} = \frac{Q}{2\pi a \cdot t} = D \frac{k_1}{a}$$

where:

$$\frac{Q}{t} = 2\pi k_1 D \quad \left(\mathrm{g\,s^{-1}} \text{ per cm of root}\right)$$

Let us now see how the previous example applies to a maize crop, logically with a series of approximations. It is a maize crop that in 3 months produces 8 tons of dry matter per hectare. The dry matter of this maize has, on average, 1.5% of nitrogen N. The number of plants is 20,000 per hectare and each one has 900 m of active roots of average diameter of 0.1 cm. Every N that reaches the surface of the root is absorbed, so in the previous equations, $C_a = 0$, which is a way to say that this soil is deficient in N. Assuming that the only process that transports nutrients until the root is the diffusion, calculate the mean concentration of the soil solution in g N cm^{-3}, at a distance of 5 cm from the roots, so that the absorption occurs constantly, without harm to plant growth. A great restriction of this example is neglecting the N mass flow due to evapotranspiration.

With the data presented, one can easily determine the absorption of N, at least in average terms:

1. Total nitrogen mass in the crop = $8000 \times 0.015 = 120$ kg N ha^{-1}
2. $\text{kg of N/plant} = \dfrac{120}{20{,}000} = 6 \times 10^{-3} \ \dfrac{\text{kg of N}}{\text{plant}}$
3. $\text{kg of N/cm of root} = \dfrac{6 \times 10^{-3} \text{ kg of N}}{90{,}000 \text{ cm of root}} = 6.67 \times 10^{-8} \dfrac{\text{kg of N}}{\text{cm of root}}$

4. kg of N/cm of root s

$$= 6.67 \times 10^{-8} \frac{\text{kg of N}}{\text{cm of root}} \times \frac{3 \text{ months}}{90 \text{ days}} \times \frac{1 \text{ day}}{86{,}400 \text{ s}} = 2.57 \times 10^{-14} \frac{\text{kg of N}}{\text{cm of root s}}$$

which means that the flow of N into each centimeter of root must have been, on average, equal to 2.57×10^{-14} kg of N s^{-1}, so that crop would establish itself and produce what it produced.

If we assume the same conditions of the previous problem, the solution will be given by Eq. (16.9) and the flow is given by:

$$j_d = -D \frac{dC}{dr}$$

derivating Eq. (16.9) in relation to r, we obtain the gradient:

$$\frac{dC}{dr} = 0 + \frac{C_a - C_b}{\ln \frac{a}{b}} \cdot \frac{1}{a} \cdot \frac{1}{r}$$

So that the flux in $r = a$ is given by:

$$j_d = -\frac{D(C_a - C_b)}{a^2 \cdot \ln\left(\frac{a}{b}\right)}$$

and for 1 cm of root of area $2\pi a$, we have:

$$\frac{Q}{t} = \frac{2\pi D(C_a - C_b)}{a \cdot \ln\left(\frac{a}{b}\right)}$$

Using the data of the exercise and considering $D = 2 \times 10^{-10}$ m^2 s^{-1}, we have:

$$2.57 \times 10^{-14} = -\frac{2\pi \cdot 2 \times 10^{-10}(0 - C_b)}{0.0001 \times \ln\left(\frac{0.1}{5}\right)}$$

$$C_b = 8.00 \times 10^{-9} \text{ kg N } m^{-3}$$

The reader must have realized that the examples seen are quite simplified and were presented here only for didactic reasons, to gain familiarity with the concepts used. These are cases of dynamic equilibrium. Most of the time, this does not happen and the equations to be solved are much more difficult, depending on each problem.

16.8 Nutrient Root Absorption

In Chap. 4, we said that the entry of nutrients into the plant can be passive (by diffusion through intercellular spaces) and active (by metabolic processes through cell membranes). In Fig. 4.8 we saw a cross section of a root. When this root is in contact with soil solution, the nutrients can diffuse into the intercellular spaces, which include the cell walls. This space is termed "outer space" (or free space) for the processes of diffusion and ion exchange between ions and the electrically charged radii of cell walls. It is separated from "inner space" (inner space or non-free space) by cell membranes, which are barriers of selective permeability. The inner space is accessible only by active transportation of the nutrients, which requires metabolic energy. The first observations that led the researchers to recognize this active transport were:

1. Nutrient uptake depends on the temperature, approximately doubling for every 10 °C increase, just as the whole metabolic process.
2. Oxygen is required.
3. The process is sensitive to inhibitors (e.g., CN^-).
4. Depends on the nature and concentration of the nutrient (e.g., K is absorbed more readily when supplied as KCl than as K_2SO_4).
5. There is interference of one nutrient in the absorption of another.

The absorption process is often adequately described by the **Michaelis-Menten equation**, which is based on the hypothesis of the **ion carriers**. This equation can be written in the form:

$$j = \frac{j_{max} \cdot C}{K_m + C} \tag{16.10}$$

where:

j = absorption rate of a nutrient in kg m^{-2} s^{-1} or mol g^{-1} s^{-1}, that is, the amount of absorbed nutrient in moles per gram of root.
j_{max} = maximum absorption rate.

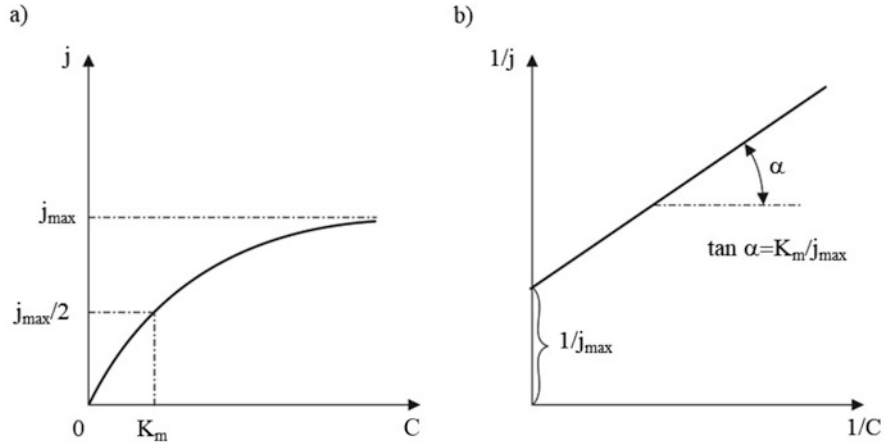

Fig. 16.2 Excised root absorption of an ion in solution, illustrated (**a**) by a graph of the ion flux j as a function of the solution concentration C and (**b**) by a graph of $1/j$ as a function of $1/C$, constructed with the same data of case (**a**)

K_m = **Michaelis-Menten constant** that gives an idea of the affinity between the nutrient and the carrier.

C = concentration of the solution in which the nutrient is absorbed.

Graphically, the phenomenon is presented in Fig. 16.2a. It is seen by this figure that j increases with C, but not linearly, having a j_{max} for high concentrations, that cannot be surpassed by biological restrictions. The value of K_m for a given plant in relation to the absorption of a given nutrient is equal to the value of the concentration for which $j = 1/2\ j_{max}$. To verify this, simply substitute j for $1/2\ j_{max}$ in Eq. (16.10) and verify that, under these conditions, $K_m = C$. The units are also identical to the units of C.

From Eq. (16.10), it can be seen that the absorption of a given nutrient by a given plant depends on the parameters j_{max} and K_m. These can be obtained in experiments in which the absorption j is studied as a function of the solution concentration C, which has been made with plants or roots placed in nutrient solutions of variable concentration. Thus, a curve of the type of Fig. 16.2a is obtained experimentally. Since it is asymptotic for values of j near the j_{max}, the latter becomes difficult to be determined precisely. The problem is circumvented by plotting $1/j$ versus $1/C$, as shown in Fig. 16.2b. In this graph, from Eq. (16.10), it is easy to verify that:

$$\frac{1}{j} = \frac{K_m}{j_{max}} \cdot \frac{1}{C} + \frac{1}{j_{max}}$$

is a straight line equation when $1/j$ is taken as the dependent variable and $1/C$ as the independent variable. Based on such a graph it is very easy to find j_{max} and K_m.

During the absorption of several nutrients, competition phenomena still appear, one element interfering with or inhibiting the absorption of another. On the other hand, for high concentrations, it seems that other absorption mechanisms start to work, since absorption may be larger than j_{max}, with another curve similar to that of Fig. 16.2a, with a second j_{max}, at high concentrations. The subject is complicated and runs away from the goals of this book. Epstein (1972) was one of the pioneers in root absorption and wrote a great text that presents details on the subject.

In the case of potassium, Yamada et al. (1982) present aspects about the availability of K in Brazilian soils, K functions in the plant, absorption mechanisms, and potassium nutrition of the main agricultural crops in Brazil. It is an example of a work that applies the concepts seen in this chapter. Havlin et al. (2014) apply the concepts seen here also for potassium and other elements.

16.9 Nutrient Balance

In the same way as we did for water in Chap. 15, we can make a balance of a given nutrient in a crop, which is the accounting for all additions and subtractions of that nutrient in a soil layer. Balances are made for any nutrient, but given the importance of nitrogen, most of the work found in the literature refers to this nutrient. In this item, we will only introduce the subject and we will talk, in particular, of the nitrogen.

Given a soil layer of thickness L (cm), the following components of the nitrogen balance are important:

1. Addition by mineral fertilizer (MF). In this case, the most common forms of nitrogen fertilizer are urea, ammonium sulfate, ammonium nitrate, sodium nitrate, etc.
2. Addition by organic fertilizer (OF). Sprays, green manures, residues from previous crops, and other organic compounds are the most common.
3. Addition by **biological fixation** of atmospheric nitrogen (BF). The legumes—common beans, soybean, etc.—have the ability, in symbiosis with microorganisms (such as *Rhizobium* spp.), to fix atmospheric nitrogen N_2 and, finally, transform it into protein. Other plants, such as grasses (poaceae), can also fix the atmospheric N_2 by a nonsymbiotic association with microorganisms found in the soil.
4. Addition by rain (AR). Small (but not negligible) amounts of nitrogen (usually in the form of ammonia) can be added to crops by rainfall. It is nitrogen transformed into ammonia during electrical discharges into the atmosphere. Today, depending on the region, air pollution can also contribute with nitrogenous compounds.
5. Addition by irrigation water (AI). Here we include only the N present in the irrigation water. The case of fertigation can be included here or in item 1, MF.
6. Extraction or export by crops (EC). Each crop, at the end of its cycle, contains a reasonable quantity of nitrogen. As the products are taken out of the area (grains, fruits, tubers, green mass, etc.), they represent loss of N to the soil. Hence the need to replenish N through fertilizers in order to maintain soil productivity.
   Even vegetable wastes are often burned in the area and, under these conditions, represent nitrogen loss. Only when incorporated into the soil is it not entirely lost.
7. Losses by volatilization (VL). It is the loss of nitrogen by passing from the solid state to the gaseous phase. It usually occurs with fertilizers: urea and ammonium sulfate can volatilize and a good proportion can be lost. Soil pH, temperature, and fertilizer application are the main factors that affect volatilization.
8. Denitrification losses (DL). Under special conditions, especially lack of oxygen, microorganisms can supply their oxygen needs using nitrates (NO_3^-). The final result of this use is N_2, passing through NO_2^-, NO, and N_2O.
9. Leaching losses (LL). Nitrogen may also be lost through the bottom of the volume element at depth L, being carried by water in the form of NO_3^-, NH_4^-, or humidified organic compounds. It is the mass flow by the deep drainage. One way to estimate the leaching is by sampling the soil solution by means of solution extractors which are made up of porous coups subjected to vacuum (Figs. 16.3 and 16.4).

When the suction probes or soil solution extractors are installed in an unsaturated soil, say with Ψ_m of the order of -100 to -200 cmH_2O, at a depth $z = L$, they do not fill with water because they are at atmospheric pressure, i.e., $\Psi = 0$. When applying vacuum to them (points A, B, and C in Fig. 16.3, the pressure inside the cup will be of the order of -1 atm or -1000 cmH_2O), and because of the potential difference $\Delta\Psi$ between the inside the cup and the soil, the solution of the soil is directed toward the capsule. The solution flow depends on $\Delta\Psi$ and the soil water content, which, in turn, determines the hydraulic conductivity of the

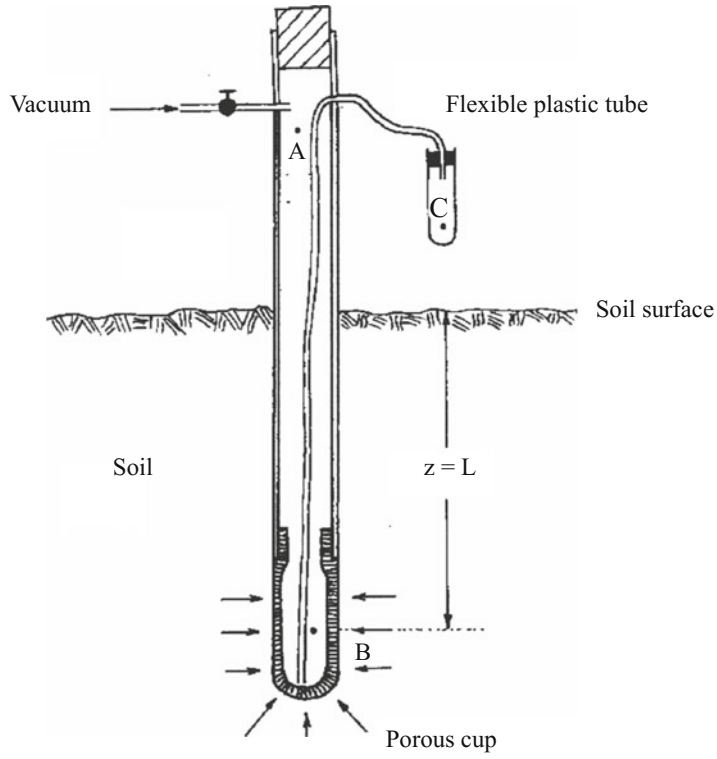

Fig. 16.3 A porous cup soil solution extractor installed at a depth L

soil. The level of the solution in the capsule rises above the point B and leaves the tip of the flexible plastic tube immersed in the extracted soil solution. After 1–2 h of vacuum (depending on the soil water content), the vacuum is disconnected and the atmospheric pressure is automatically exposed to point A. Since C is still under vacuum, the solution rises and will fill the test tube. It is a clear solution, ready for analysis of ionic concentrations C_i. As we saw in Chap. 8, the product of water flow density q, by concentration C_i, gives us the flux density of solute j. If these instruments are used in conjunction with tensiometers, as shown in Chap. 15 and in Fig. 16.4 for the determination of the deep drainage, one can estimate the quantities of leached solute.

From the algebraic sum of the nine previous items results the N storage (or its variation) (ΔA_N) in the considered layer 0–L (see Eq. 3.22, Chap. 3). Even with no additions or losses, the nitrogen in this layer is extremely dynamic. By the process of mineralization, it goes from organic to mineral; by absorption processes by microorganisms it can pass from mineral to the organic phase. NO_3^- can be adsorbed by positive charges of the soil and NH_4^+ by negative charges. Thus, the amount of N available to the plants in the soil solution is quite variable. The processes that determine this availability are complex and interdependent.

The nitrogen balance (Fig. 16.5) can then be written in the form:

$$\mathrm{MF} + \mathrm{OF} + \mathrm{BF} + \mathrm{AR} + \mathrm{AI} - \mathrm{EC} - \mathrm{VL} - \mathrm{DL} - \mathrm{LL} \pm \Delta A_N = 0 \tag{16.11}$$

in which it is seen that the number of components is much larger than in the case of the water balance.

The literature on **nitrogen balance** or on the various components of the balance sheet is vast and we will not make a review here. Just as an example, we indicate some work done in Brazil.

Fig. 16.4 A sugarcane crop showing in the front two tensiometers and in the back center a soil solution extractor

Reichardt et al. (1977) discuss the problem of extraction and analysis of nitrates in the soil solution; Libardi and Reichardt (1978) studied the fate of urea applied to a bean culture using ^{15}N as a tracer; Reichardt et al. (1979) presented the dynamics of nitrogen in a corn crop; Cervellini et al. (1980) and Meirelles et al. (1980) studied the fate of ^{15}N applied as ammonium sulfate to a bean crop; and Reichardt et al. (1982) reviewed the nitrogen balance in tropical crops. Reichardt (1990) discussed the problem of soil spatial variability in the estimation of biological nitrogen fixation (FB).

Interesting contributions in this area were given by Fenilli et al. (2007b), who evaluated the losses of N by volatilization of the urea fertilizer in a coffee crop, and Fenilli et al. (2007a), which present a complete balance of a coffee crop conducted in Piracicaba. Bruno et al. (2011) present urea nitrogen uptake data for 1 year in fertigated coffee in western Bahia, Brazil. With the same data from the previous work, Bruno et al. (2015) present the complete balance of the crop of fertigated coffee.

16.10 Use of Isotopes in Agricultural Experimentation

Isotopes, both stable and radioactive, have been successfully used as tracers or markers of their respective elements. Each element of the periodic table has isotopes—atoms of the same species—behaving chemically and biologically in the same way, differing only in some physical properties. They have in the nucleus the same number of protons (which defines the element), but a different number of neutrons, which makes them different in terms of mass. Its majority is natural, being present in nature since the formation of our planet Earth; some are artificial, produced in the laboratory by nucleation reactions. When stable, they differ only in atomic weight and, when radioactive, emit radiation. The important thing is that both differ in a measurable way and can be detected. **Stable isotopes** are detected by **mass spectrometers**, instruments capable of distinguishing atomic weights. **Radioactive isotopes** are detected by radiation detectors, which include a series of instruments, depending on the type of radiation emitted by the radioisotope. Radioisotopes are unstable isotopes that seek their stability by emitting radiation. These can be detected easily and in minimal quantities, i.e., at concentrations as low as 10^{-11} (about 1–-100 billion). Each radioisotope has its own characteristics and emits one or more types of radiation (in particular α, β^-, β^+, γ, and neutrons), with one or more energies and at a rate that depends on their **half-life**. As this rate decreases exponentially over time, the half-life $T_{1/2}$ has been defined as the time required for any emission rate to be reduced to its half. Depending on these properties, each radioisotope is suitable (or not) for different uses as a tracer. The type and energy of radiation affect the detection. A short half-life may limit its use in longer duration experiments.

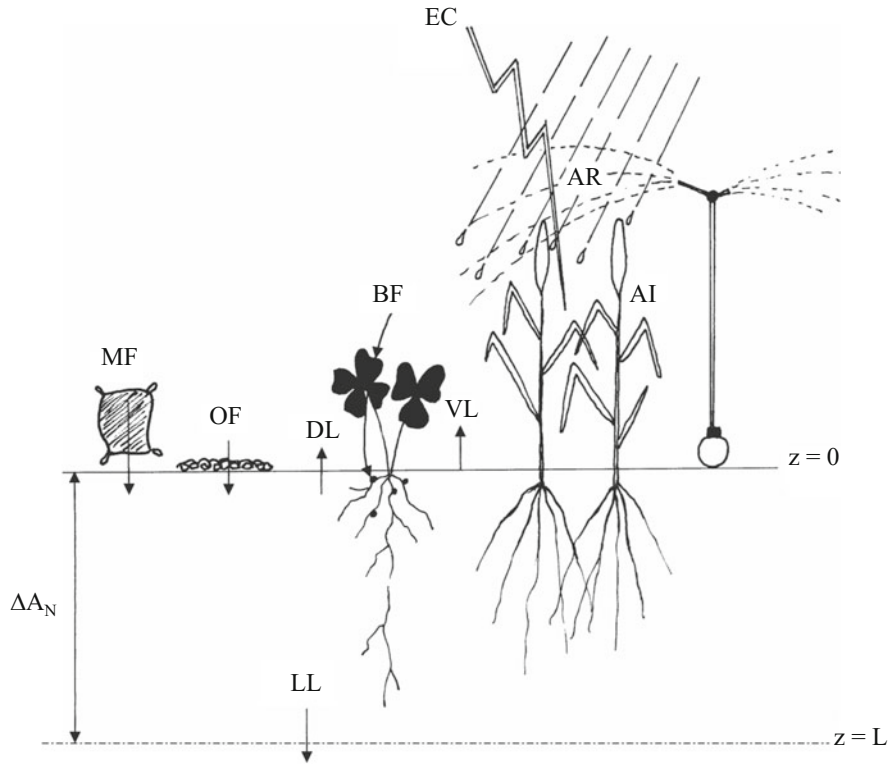

Fig. 16.5 Illustration of a nitrogen balance: *MF*, mineral fertilizer; *OF*, organic fertilizer; *DL*, denitrification loss; *BF*, biological N fixation; volatilization loss; *EC*, electric discharges; *AR*, irrigation water contribution; *AI*, crop export; *LL*, leaching at depth *L*; and ΔA_N, the change in soil N storage during the period of the balance

Radioisotopes are found in nature, as is the case of ^{3}H (tritium), ^{14}C, ^{40}K, ^{226}Ra, ^{235}U, and others; some are produced continuously by nuclear reactions that occur in the atmosphere by interaction of solar or cosmic radiation with dispersed atoms, such that their rate of production is in equilibrium with the rate of radioactive disintegration, thus presenting a constant global content, as is the case with ^{14}C; others have half-lives longer than the age of our planet and are still present in the environment and are made up of radioactive series beginning with uranium, thorium, and actinium, passing, for example, by ^{226}Ra, finishing with some isotope of lead. The vast majority of radioisotopes used as tracer are, however, artificially produced in nuclear reactors. Table 16.2 shows the main radioisotopes used as tracers in the SPAS. To use them as tracers, they are added to their stable isotope in amounts that allow their detection until the end of the experiment. When possible, they should be added in the same chemical form in which the stable compound is present and thus become true tracers. If a phosphorus study involves superphosphate, the ^{32}P radioactive isotope must also be present in the form of superphosphate. This is sometimes more difficult, as in the case of studies with herbicides, in which ^{14}C should be incorporated into the complex molecule of the respective pesticide.

The intensity of radioactive materials is measured in terms of **radioactive activity** (Bequerel, 1 Bq = 1 disintegration/s, Curie, 1 Ci = 3.7×10^{10} disintegrations/s). Since each detected radiation corresponds to a count in the measuring instrument, the activity is also measured in counts per second (cps) or counts per minute (cpm). In addition, because the measured activity depends on the sample size (extensive magnitude), the activities are also

Table 16.2 Most important radioisotopes used in agricultural research

More abundant isotope	Tracer radioisotope	Energy of radiation (MeV)		Half- life
		Beta	Gamma	
Calcium-40	^{45}Ca	0.254		153 days
Carbon-12	^{14}C	0.156		5720 years
Cesium-133	^{137}Cs	0.52; 1.18	0.662	30 years
Cobalt-59	^{60}Co	0.31	1.17; 1.33	5.27 years
Strontium-88	^{89}Sr	1.47		50.4 days
Sulfur-32	^{35}S	0.168		86.7 days
Hydrogen-1	^{3}H	0.0181	0.36; 0.08; 0.72	12.26 years
Iodine-127	^{131}I	0.61; 0.25; 0.85	0.032; 1.35; 0.95	8.05 years
Magnesium-24	^{28}Mg	0.45	0.94; 1.46	21.3 h
Manganese-55	^{52}Mn	0.60		5.7 days
Phosphorus-31	^{32}P	1.71	1.46	14.3 days
Potassium-39	^{40}K	1.32	1.08	1.3×10^9 years
Rubidium-85	^{86}Rb	0.7; 1.77		18.7 days
Zinc-64	^{65}Zn	0.33	1.11	245 days

expressed in terms of the specific activity s_a, which is the activity per unit mass or volume, i.e., cps g^{-1}, cpm g^{-1}. The use of isotopes in experiments covers a wide range of forms, from the simple presence of the tracer at a given point in the system until its follow-up in dynamic studies. The basis of most applications is the principle of **isotopic dilution**, whereby "given a constant amount of radioactivity, the specific activity is inversely proportional to the total element or substance present in the system." This means that for a fixed amount of $^{40}CaCl_2$, the more stable compound $CaCl_2$ is added, the lower the specific activity of the blend (when homogeneous). This principle allows, for example, to estimate the amount of a nutrient in a plant, which came from the fertilizer applied to the soil. If a phosphate fertilization study uses ^{32}P-labeled superphosphate, one can make for the P that is in the plant a distinction between the one that comes from the fertilizer and the one that comes from the soil. In this case, the phosphorus derived from the fertilizer (Pddf) is defined, which can be calculated by the expression:

$$\%\text{Pddf} = \left(\frac{s_a \text{ of } ^{32}\text{P in the plant}}{s_a \text{ of } ^{32}\text{P in the fertilizer}} \right) \times 100 \tag{16.12}$$

If a soil is fertilized with a fertilizer that contains a specific activity $s_a = 102{,}441$ cps/μmol P and a plant is grown on it, the plant is exposed to sources of P, the labeled fertilizer, and the native soil P which is not radioactive. It is easy to understand that if the plant only absorbs P from the fertilizer, in the end its specific activity would be equal to that of the fertilizer. On the contrary, if it absorbs only P from the soil, its specific activity would be $s_a = 0$. As it absorbs from both, and according to the availability of each, its value of s_a will be intermediate. Taking the plant and measuring its s_a, for example, 35,758 cps/μmol P, we would have % Pddf = (35,758/102,441) × 100 = 35%, which means that of all P found in the plant, 35% came from the fertilizer and 65% from the soil. If the total extraction of the crop was of 15 kg ha^{-1} of P, 0.35 × 15 = 5.25 kg ha^{-1} of P came from the fertilizer and 9.75 comes from the soil. The efficiency of the fertilization was (5.25/60) × 100 = 8.75%, if the fertilization was 60 kg ha^{-1} of P.

It can be seen that, with the use of markers, fertilization efficiency, fertilizer application optimization, rates, times, crop responses, etc., can all be studied.

Stable isotopes can also be used for the same purposes. Not always a certain element has a

Table 16.3 Most commonly used stable isotopes in agricultural experimentation

Element	Isotope	Isotopic abundance
Carbon	^{12}C	99.985
	^{13}C	0.015
	^{14}C	Traces
Hydrogen	^{1}H	98.89
	^{2}H	1.11
	^{3}H	Traces
Nitrogen	^{14}N	99.635
	^{15}N	0.365
Oxygen	^{16}O	99.759
	^{17}O	0.037
	^{18}O	0.204
Sulfur	^{32}S	95.0
	^{33}S	0.76
	^{34}S	4.22
	^{36}S	0.014

suitable radioisotope and there is made use of the stable isotope, with the advantage of not being radioactive. Table 16.3 shows the most used ones.

The basis of the use of stable isotopes lies in the concept of **isotopic abundance**. Abundance is the proportion in which the isotopes of a given element appear in nature. The nitrogen element, for example, has only two stable and natural isotopes, ^{14}N and ^{15}N. The abundance of ^{15}N in a sample is:

$$\%\ ^{15}\text{N atoms} = \left(\frac{\text{number of } ^{15}\text{N atoms}}{\text{number of } ^{15}\text{N} + ^{14}\text{N atoms}}\right) \times 100 \tag{16.13}$$

Since N is a very dynamic element in SPAS, abundances of ^{14}N and ^{15}N are practically constant and the same in any biological sample. Their values are 99.635% for ^{14}N (more abundant) and 0.365% for ^{15}N. Samples can be enriched in ^{15}N by special laboratory techniques, and the amounts of ^{15}N in enriched samples can be expressed in terms of % excess atoms over the natural abundance of 0.365%.

Dynamic processes in which the flow of nitrogenous compounds is affected by the atomic weight discriminate the ^{14}N of the ^{15}N. This phenomenon is used in the laboratory to enrich samples in ^{15}N. Using batteries of long ion exchange columns, ammonium sulfate can be enriched in ^{15}N. In this way, we can have a compound like a nitrogen fertilizer, enriched at high levels of ^{15}N, for example, a sample of ammonium sulfate with an abundance of 10.365% of ^{15}N. Its abundance in ^{14}N is 89.635% and it has 10.000% atoms in excess of ^{15}N.

This fertilizer can be used as a tracer in agronomic studies. If a soil is fertilized with this material, the crop established there is exposed to two sources of nitrogen at its disposal: the native N of the soil with abundance of 0.365% and the fertilizer with abundance of 10.365%. As the crop makes use of both sources, in proportion to their availability, we can also calculate the **nitrogen derived from the fertilizer** (Nddf), given by the expression:

$$\%\ \text{Nddf} = \left(\frac{\%\ ^{15}\text{N atoms in excess in the plant}}{\%\ ^{15}\text{N atoms in excess in the fertilizer}}\right) \times 100 \tag{16.14}$$

If, for example, the plant grown on the soil shown above presents an abundance of 7.855%, it will have a value of ^{15}N atoms in excess of $7.855 - 0.365 = 7.490\%$ and Nddf% = (7.490/10.000) × 100 = 65%. Its interpretation is the same as Pddf.

Important studies performed in Brazil that used ^{15}N as a tracer are those of Fenilli et al. (2007a, c), Bortolotto et al. (2011), and Bruno et al. (2011).

Legumes have a third source of nitrogen, the atmospheric N_2, absorbed in symbiosis with bacteria *Rhizobium* spp. Which form nodules at their roots. When it is desired to make a distinction of this **biological nitrogen fixation** (BNF), it is necessary to cultivate a N_2 non-fixing plant next

to the legume, in the same soil fertilized with ^{15}N. Although it is not a legume, it should have similar size and development, so that the comparison would be reasonable. In many cases, a grass is used, such as wheat, barley, and oats, but with the discovery of the nonsymbiotic fixation of atmospheric nitrogen by the poaceae (grasses), especially sugarcane, the non-fixing plant should be well thought out. Imagine that in the previous example, the plant was barley and that soybean plants grown in the same situation had an abundance of 5.136%. The abundance of soybeans is lower because it has three N sources and therefore absorbs less labeled fertilizer. In this case, the nitrogen derived from the atmosphere (Ndda) is calculated by the expression:

$$\%\text{Ndda} = \left[1 - \left(\frac{\%\ ^{15}\text{N atoms in excess in the legume}}{\%\ ^{15}\text{N atoms in excess in the non fixing plant}}\right)\right] \times 100 \qquad (16.15)$$

and, in the example, we would have Ndda % = [1 − (4.771/7.490)] × 100 = 36.6%. Thus, from the N contained in soybean, 36.6% came from the atmosphere, and the remaining 63.4% came from both the soil and the fertilizer, in a proportion that cannot be calculated and, of course, different from that of the barley.

The Nddf concept can be applied to any N compartment in the crop, as long as each is sampled separately. In a study with sugarcane with ^{15}N, started in 1997 and in which the tracer could be followed for 5 years, Basanta et al. (2003) separately calculated the Nddf for leaves, straw, stems, soil, and soil solution, following the "pulse" of fertilizer applied to the cane plant, until the third ratoon, succeeding in making a nitrogen balance. The labeled cane plant straw was also used as mulching and could be followed by its mineralization over the years. This study was later compared to the mineralization of crop residues from several tropical regions in the world by Dourado-Neto et al. (2010).

The concept of **A Value** of a soil, which refers to the availability of nutrients, especially in relation to nitrogen and phosphorus, is also linked to the use of isotopes. Very good manuals for these applications of nuclear energy in agriculture are those of Vose (1980), L'Annunziata (1998), Hardarson (1990), and IAEA (2001).

Another way to use stable isotopes as tracers is by means of small (but significant) natural variations in abundance. As we have already said, dynamic processes occurring in the SPAS lead to isotope discrimination. In the first exercise of Chap. 2, we saw the 18 types of water molecules, which differ only in weight. When water is lost from a Class A tank, the phase change process discriminates the 18 types, and the lighter ones evaporate more easily. Thus, after some time, the water remaining in the tank is somewhat enriched in ^{18}O and ^{2}H. In other dynamic processes there is also discrimination of ^{15}N in relation to ^{14}N, ^{13}C in relation to ^{12}C, and so on. As these abundance variations are very small, a more sensitive measure is used, which is the **isotopic ratio** given in δ values. For the $^{13}C/^{12}C$ relationship, for example, the value of δ is calculated by:

$$\delta^{13}\text{C‰} = \left[\left(\frac{^{13}\text{C}/^{12}\text{C in the sample}}{^{13}\text{C}/^{12}\text{C in the standard}}\right) - 1\right] \times 1000 \qquad (16.16)$$

and standards are reproducible and internationally chosen samples. The most commonly used isotopic ratios are $^{2}H/^{1}H$, $^{13}C/^{12}C$, $^{15}N/^{14}N$, and $^{18}O/^{16}O$ (Table 16.3). The plants discriminate the C isotopes in the photosynthetic process. **C3 plants** (see Chap. 4) have values of $\delta\ ^{13}$C‰ in the range of −11 to −14, while **C4 plants** from −25 to −30 C‰. This fact makes possible the study of interesting aspects in the carbon cycle in different ecosystems, as it is done in the comparison of carbon storage (or carbon stock) in the soil in tropical natural forests (mainly C4 species) and in introduced pastures (mainly with C3 plants).

Even differences in cattle grazing (between grasses and legumes) can be studied by the δ ^{13}C values found in their feces.

The use of the δ ^{13}C ratio is also very useful in studies of the **global carbon balance** in the atmosphere. The increase in CO_2 concentration in atmospheric air is a concern with regard to the **global changes** that occur on planet Earth, including the **greenhouse effect**. In the carbon balance, CO_2 emissions from burning fossil fuels are important and, from the agricultural point of view, the shift from forest areas to pasture and agricultural crops, which also causes emissions by burning the carbon stock contained in the forests of stable form. **Carbon sequestration** is done by photosynthesis, mainly by seaweed, forests, pastures, and agricultural crops. The balance between emission and sequestration defines the levels of CO_2 in the atmosphere. Cerri et al. (1991) is an example of a study of this nature and Rosenzweig and Hillel (1998) deal with the subject in a global way.

The main controversy over the causes of **global warming** is the question if the rise in air temperature recorded in recent decades is caused by natural global processes or **anthropogenic** influence through increases in CO_2 concentration in the atmosphere caused by the burning of petroleum and coal. Kutilek and Nielsen (2010) dealt with this subject with propriety, making an analysis of climate variations from prehistory to now.

Hydrological studies make use of δ ^{18}O in very varied ways. The value of δ ^{18}O is different for seawater (taken as standard) and freshwater to such an extent that different water colors may present consistent differences. As an important example, we cite Matsui et al. (1976) who measured the proportion in which the Solimões and Negro rivers of the Amazon basin contribute to the formation of the Amazon River.

Other applications of nuclear tools were already presented in Chap. 6, like gamma ray attenuation, neutron probes, and soil tomography. An excellent review on **soil tomography** was recently published by Pires (2018).

16.11 Exercises

16.1. If you had to organize an example such as page 319 of this Chapter with a bean crop, what data would you use for dry matter per hectare production, % nitrogen, plants per hectare, root system length, and average root diameter? What would be the flow of nitrogen per centimeter of root per second?

16.2. In a root absorption experiment, the following results were obtained:

j (mol g^{-1} s^{-1} $\times$ 10^{15})	C (mol L^{-1} $\times$ 10^{3})
4.6	0.5
7.8	1.0
11.1	2.0
14.6	4.0
17.5	7.0
19.1	10.0
19.6	15.0
19.8	20.0

Make the graphs of j versus C and $1/j$ versus $1/C$ to estimate the values of K_m and j_{max}.

16.12 Answers

16.1. 5000 kg; 3%; 125,000; 500 m; 0.05 cm; N flux $= 4.63 \times 10^{-12}$ for a 60 day cycle.

16.2. $j_{max} = 2.2 \times 10^{14}$ mol g^{-1} s^{-1} and $K_m = 1.89 \times 10^{-3}$ mol L^{-1}.

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